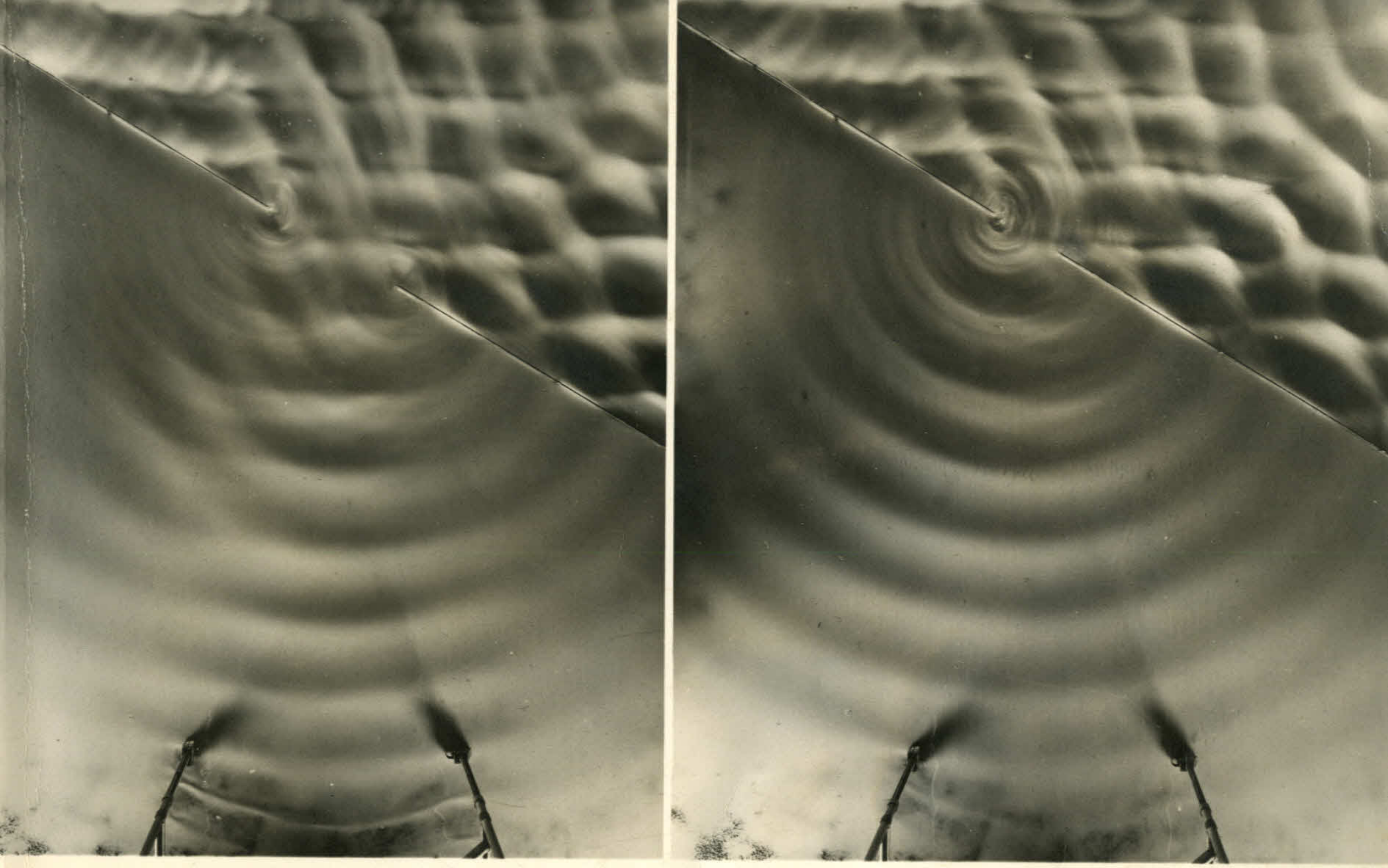

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HARBOR DEVELOPMENT STUDY

Progress Report for August - October, 1950

CALIFORNIA INSTITUTE OF TECHNOLOGY

Hydrodynamics Laboratories, Hydraulic Structures Division

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Progress Report for August 1 - October 31, 1950

H A R B O R   D E V E L O P M E N T   S T U D Y

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The Cover

The cover photographs illustrate the effect of gate size on wave crest alignment in the lee of a breakwater opening. These examples for 60° incidence are typical for openings in straight or symmetrically inclined breakwaters; the crest alignments become circular arcs centered at the opening at distances greater than a minimum of about three gap widths. The knowledge of crest alignment is necessary for the solution of problems involving combined diffraction and refraction.

PROGRESS REPORT ON THE GENERAL HARBOR STUDY

FOR THE PERIOD FROM AUGUST TO OCTOBER 1950

I. INTRODUCTION

This report summarizes the results of the first phase of the Laboratory's current comprehensive study of harbor design. This phase comprises the study of the transmission of wave energy through, and the distribution of wave energy behind, breakwater openings. The results obtained to date relate the effect of three major variables; width of breakwater opening, direction of wave approach, and breakwater alignment, on the two quantities mentioned above. The results of this study are subject to certain limitations, notably the small number of cases studied, the idealization of harbor and breakwater configuration, and experimental error. However, the results are considered to be far more quantitative than qualitative and to be of definite usefulness and value in harbor layout and design.

The course of the experimental investigation has been greatly influenced by the theoretical work of Morse and Rubenstein on the diffraction of waves incident on ribbons or slits of dimensions comparable to the wave length. Thus, the representation of the energy distribution in the lee of a breakwater by means of a polar plot of a dimensionless wave energy "intensity factor" is due to these investigators. The fact that reasonable agreement of experimental and theoretical results was obtained in the cases for which the theory can be applied is an excellent verification of the validity of the experimental results for the many other cases herein presented and which may be investigated in the future - cases for which the theoretical approach, by reasons of breakwater geometry, cannot be applied. A complete discussion of the theoretical approach of Morse and Rubenstein, as well as other pertinent theoretical considerations, is contained in the Progress Report of this Laboratory dated June 1950.

The number of cases studied was necessarily limited by time considerations. Accordingly, most effort was concentrated on a thorough study of the basic configuration of a vertical face, straight breakwater, since this is the case most susceptible to theoretical analysis. The range of variables studied for this breakwater configuration included three widths of opening ($\frac{1}{2}$, 1, and 2 wave lengths) and six directions of wave approach (90°, 60°, 45°, 30°, 15°, and 0°). Other conditions studied included straight breakwaters of trapezoidal cross section with $1\frac{1}{2}$: 1 side slopes (1 and 2 wave length openings; 90°, 60°, 30° wave approach), vertical face breakwaters with symmetrically inclined arms enclosing 120°, 90°, 60°, and 30° sectors (1 and 2 wave length openings, wave approach along the center line of symmetry), and vertical face breakwaters with arms at right angles, with varying degree of overlap (1 and 2 wave length openings, wave approach at 90° to one arm, 0° to other). All conditions studied are shown diagramatically in Fig. 1.

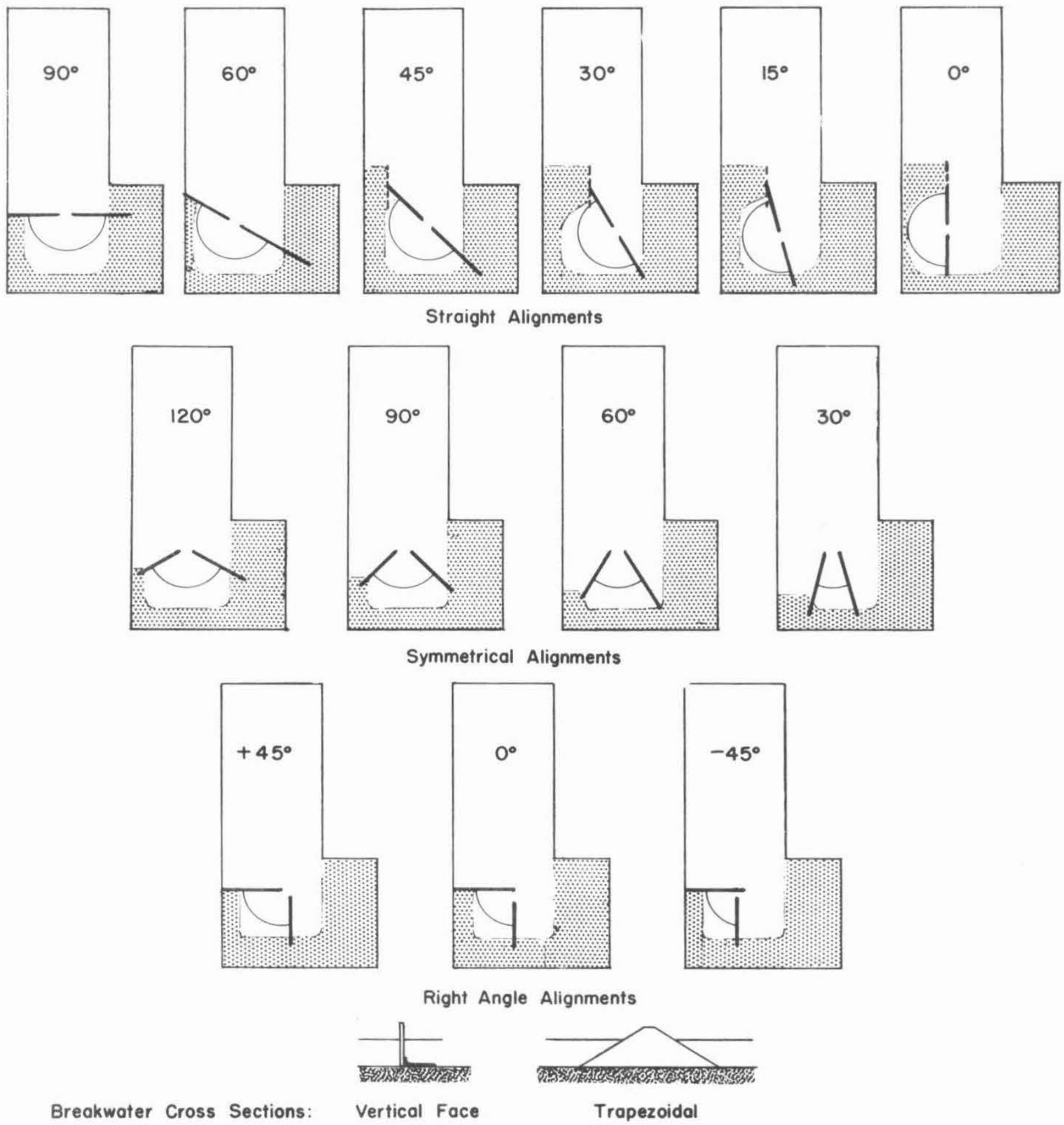

FIG. I — SCHEMATIC OUTLINES OF BREAKWATERS

II. EXPERIMENTAL METHOD

A. Equipment.

The test basin used for the experimentation is described in the progress report for June - December 1949, however, it may be well to repeat its dimensions. The basin is L-shaped with an overall east-west length of 61 feet. A 20-foot pneumatic wave machine is stationed at the west where the water depth is 12 inches. The channel is 20 feet wide for 37 feet and has a bottom slope of 2.4 per cent. The remaining length of 24 feet has a level bottom, with 3-inch water depth, and is 32 feet 4 inches wide. This increased width was provided to permit the installation of absorbing beaches. These beaches are needed to prevent waves, which are reflected from breakwaters inclined to the direction of wave propagation, from re-entering the area being studied. Beaches were used also around the periphery of the harbor for the same purpose. The beaches were of pea gravel with a slope of from 8 to 16 per cent extending approximately one inch above the water surface. Fig. 2 is a photograph of the basin.

The breakwaters were built of 3/8" thick by 5 inch high Plexiglas sections, 2 and 4 feet long. The Plexiglas was bolted to angles with a $3\frac{1}{2}$-inch wide horizontal leg to provide stability and prevent sliding, and a 1-inch vertical leg to decrease loss of transparency. The transparent construction of the breakwater sections was adopted for photographic purposes. The Plexiglas sections were attached to the angles in such a manner that the Plexiglas joints overlapped the angle joints,

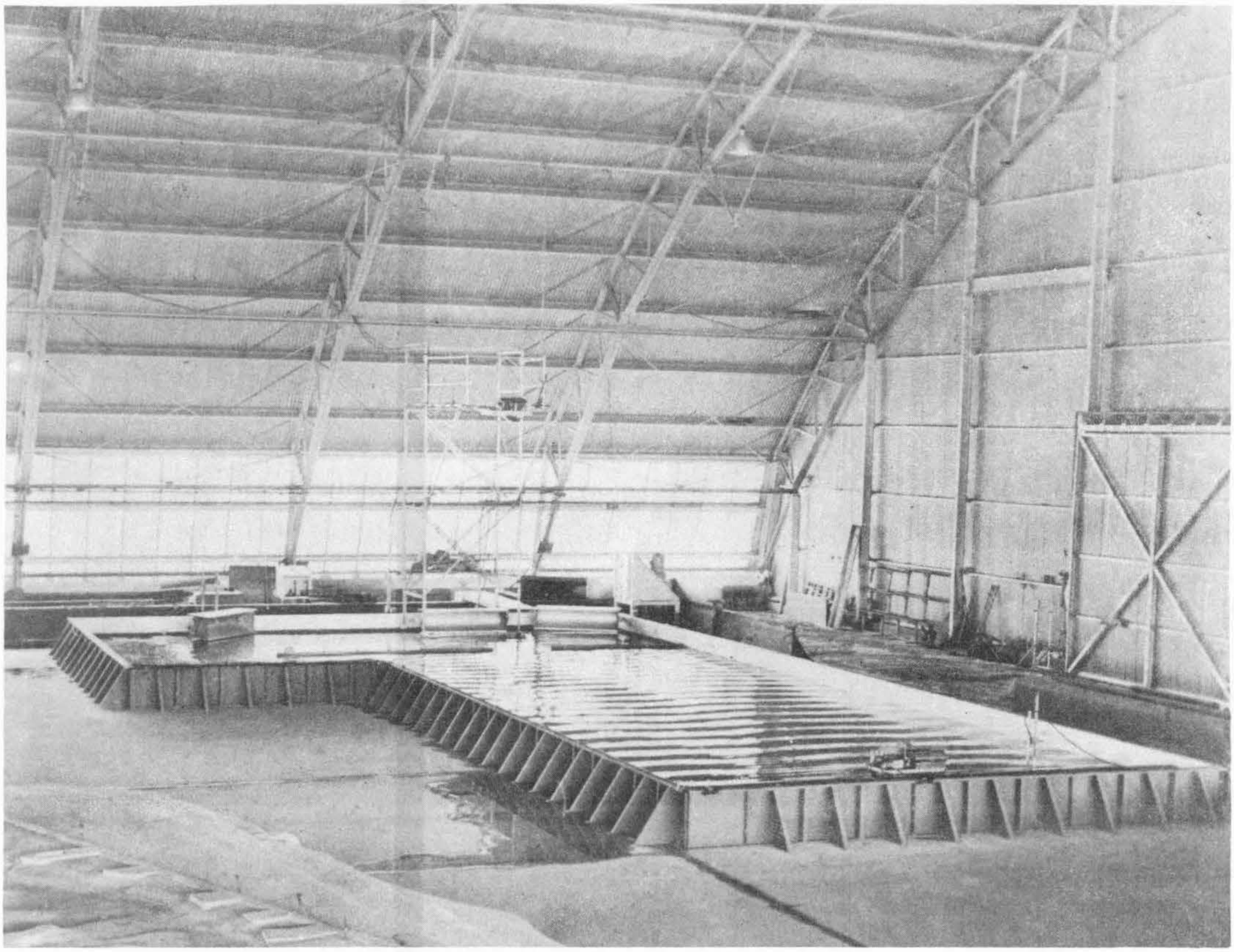

FIG. 2 — TEST BASIN AND CAMERA TOWER

resulting in a fairly rigid member. Lines were laid out with a transit on the basin floor so that the breakwater could be placed later, making angles of 90, 60, 45, 30, 15, and 0 degrees with the direction of wave propagation. The breakwaters extended into the wider area of the basin in all cases, with the waves reaching the breakwater opening after travelling 7 to 9 feet through shallow water first. In the case of the smaller alignment angles the breakwaters were not extended to the southern basin wall but were terminated at a wave splitter installed parallel to the wall. This splitter was built of 20-gage Terne plate, with a beach provided between the splitter and the basin wall.

Wave heights were measured with electrical conductivity elements and the associated recording oscillograph. This equipment is fully described in "Model Studies of Apra Harbor" by this Laboratory. The measuring elements were suspended from a framework, called the array, which in turn was supported by four 3/8-inch diameter legs resting on the basin floor. The array is essentially a coordinate system in which a number of elements can be mounted to describe any desired curve.

B. Study of Transmitted Wave Energy.

In order to determine the distribution of wave energy in the lee of the breakwater, it was desirable to measure the transmitted wave energy at large distances - say 10 wave lengths - from the breakwater opening, to insure that the radius of curvature of the wave crests be sufficiently large that the waves behave essentially as plane waves. Since the physical dimensions of the basin were fixed, this consideration imposed an upper limit on optimum wave length to be used. Subsequent investigation, however, established a lower limit on wave length in excess of this upper limit, this limitation being set be the occurrence of abnormal friction losses for waves shorter than this limiting value. The value of wave period selected - 0.55 sec. - resulted in a wave length of 1.3 feet in the 3-inch harbor water depth, hence the maximum possible measuring radius of 7.5 feet as dictated by the size of the basin was equal to 5.76 wave lengths.

This condition proved satisfactory, however, theoretical analysis showing the waves at this distance to approximate the behavior of plane waves with very little error. Experimental measurements were made to verify this analysis, consisting of wave height measurements along radial lines outward from the center of the breakwater opening. For plane wave behavior the wave height should vary inversely as the square root of the distance from the opening, and the curves of Fig. 3 show this relationship to occur for distances greater than 3 or 4 wave lengths. It will be observed that curves "A" of the lower half of Fig. 3 dip below the theoretical values for large distances; this is believed due to experimental difficulties, however, and is not construed as indicating a departure from theory. Thus, reference to Fig.10 shows that alignment "A" is in a region where the intensity factor, I, changes very rapidly with angle, hence the inherent lack of complete stability of wave patterns is greatly magnified in this region, and experimental measurements may be expected to exhibit rather wide scatter.

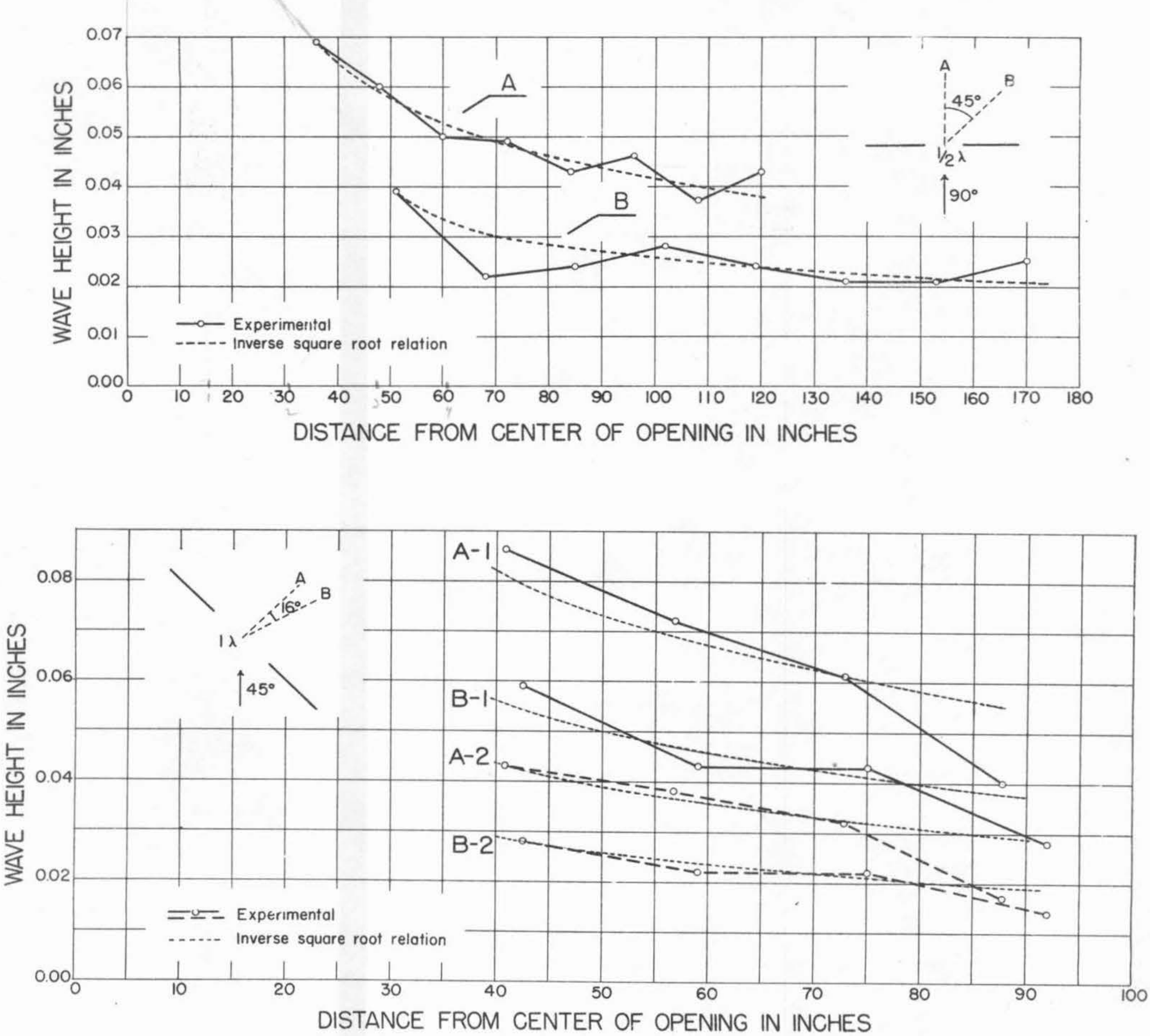

FIG. 3 — RADIAL VARIATION OF WAVE HEIGHTS IN LEE OF BREAKWATERS

Since the complete 180° of arc along the measuring semi-circle could not be covered at one time with the desired closeness of measuring element spacing due to the limited number of recording channels available, each run required shifting the array successively into four quadrants with the result that measurements were made approximately every 4 degrees of arc. The highest numbered element in a quadrant occupied the position of the lowest numbered element in the preceeding quadrant, this "tie point" insuring continuity of the four parts of each run. For each breakwater and array position, a total of three runs were made before the array was moved into the next quadrant and the results averaged in the final computations. During the entire series of runs with the six different breakwater alignments, each with openings of $\frac{1}{2}$, 1, and 2 wave lengths, the blower equipment (regulating wave height) and the oscillating valve equipment (regulating period) were left undisturbed so that, together with the careful adjustment of the water surface to 0.001 feet, the imposed wave conditions were as uniform as possible. This did not, however, preclude differences in the height of the imposed waves of up to 15 per cent.

C. Incident Wave Energy.

Four wave measuring elements were installed at a position approximately 9 feet from the wave machine, in an average water depth of 0.77 feet, to measure the incident wave height. These elements were arranged in a line parallel to the direction of wave travel, and spaced one-quarter wave length apart. With this arrangement, the presence of a standing wave in the basin (due to reflections) is indicated by differences in readings of the four elements. By inspecting the oscillograph records of incident and transmitted wave motions, the time at which secondary reflections become noticeable could be determined and the transmitted wave heights measured prior to this time. Thus the data is essentially the same as if collected in a basin of infinite extent in which secondary reflections (those other than from the breakwater) do not occur.

The evaluation of breakwater performance is in terms of the transmitted wave height and the wave height incident at the breakwater. The latter quantity is related to, but not equal to, the deep-water wave height measured in the experiments. Calculations indicated that the wave height in the 3-inch water depth should be 92% of the deep-water height, due to the effect of shoaling. However, experiments showed this factor to be 75% for the conditions studied; the additional height decrease apparently being a manifestation of fluid friction damping not allowed for in the theoretical calculation. The experimental procedure adopted for determining the change in wave height between the deep and shallow regions of the basin consisted of causing complete reflection of the incident waves by a vertical barrier in the shallow water region and measuring the height of the resulting standing wave, which must equal twice the height of the incident wave.

D. Evaluation of Data.

The submergence elements, together with their respective circuits, were adjusted for sensitivity and calibrated before each day's work and re-calibrated at the conclusion of each day's run. In most cases slightly different sensitivity factors were computed for each element circuit and the data from each circuit were therefore adjusted individually.

The oscillograph records on photo-sensitive paper. The 16 traces, portraying the variation of the water surface of the given points with respect to time were read by means of a parallel rule, calibrated to 0.02 inch, so that readings to 0.01 inch could be obtained. The calibration ratio was approximately 6:1, i.e. a variation in the water surface of 0.05 inches, for instance, would result in a difference in reading of 0.30 inches on the record. Since the reading error is assumed to be independent of wave height and not to exceed 0.01 inches it can be seen that the determinations of the variations in the water surface are fairly accurate.

The data were processed to show the energy distribution in the harbor by means of polar plots, as developed by Morse and Rubenstein, with radius proportional to an "Intensity Factor", I, which is equal to the ratio of the wave height squared at the given point inside the harbor to the wave height squared incident at the breakwater opening, multiplied by the distance in wave lengths from the center of the opening to the measuring point. In terms of the measured quantities, where the wave height incident at the breakwater, H_o, is taken as 75%

of the measured deep-water height, H_o';

$$I = \frac{(H_i)^2}{(.75\ H'_o)^2} \times \frac{R}{\lambda}$$

Physically, I may be thought of as the ratio of transmitted to imposed energy intensity at unit distance inside the breakwater, although actually the values of I found by theory and/or experiment do not hold at such short distances from the opening. The significance of I is that for all distances greater than some minimum, which appears to be of the order of 4 or 5 wave lengths for the range of breakwater opening widths herein considered, the value of I in any given direction, I_θ, is constant, and the energy ratio, $\frac{H_i^2}{H_o^2}$, at any distance R_x from the opening is obtained by dividing the Intensity Factor by the distance:

$$\frac{H_i^2}{H_o^2} = \frac{I_\theta}{R_x/\lambda}$$

The wave height at this point, in terms of the wave height incident at the breakwater, is therefore:

$$H_{i_x} = \sqrt{\frac{I_\theta}{R_x/\lambda}}\ H_o$$

Attention is called to the fact that in the work of this Laboratory, as in this report, the unit of distance is taken as the wave length. Morse and Rubenstein, on the other hand, use the breakwater opening, d, as the unit of distance. Thus, values of I contained in Morse and Rubenstein's publications must be multiplied by the factor $\frac{d}{\lambda}$ to be comparable to the Laboratory's experimental work. This conversion has been performed on all theoretical values presented in this report.

The values of total transmitted energy are obtained by numerically integrating the product of transmitted height squared times arc distance along the measuring circle. The transmission factor T may thus be expressed as:

$$T = \frac{\int_0^{\pi} H_i^2 \, R \, d\theta}{(.75\, H_o')^2 \, d}$$

III. DISCUSSION OF RESULTS

A. Energy Transmission.

The effect of the parameters of breakwater alignment, direction of wave approach and width of opening on total energy transmission are shown in Figs. 4,6,7 and 8. Following the notation of Morse and Rubenstein, these data are plotted in terms of a transmission factor, T, which is the ratio of the total energy admitted to the amount of energy which would pass through the opening at normal (perpendicular) incidence in the absence of any diffraction effects. Thus, in the absence of any diffraction effects, T would be independent of size of opening and equal to the sine of the angle between the breakwater and the direction of wave travel. In this regard, it may be noticed that as the width of opening is increased, with resulting decrease in the contribution of diffraction to the overall energy transfer, both theoretical and experimental curves become asymptotic to the same value.

In general the experimental values for vertical-face, straight breakwaters exhibit the same shape of curve as the theoretical, but are in all cases of lower values. The extent of the deviation between theory and experiment is indicated in Fig. 5, where the average of the ratio of measured to computed transmission at each of the three measuring points ($\frac{1}{2}$, 1, and 2 wave lengths) are plotted as a function of wave approach angle. It is seen that with the exception of the 30° case, which must be considered "sour", the average deviation is remarkably constant, with a ratio of 0.80, for approach angles up to 15°, and that the 0° case is

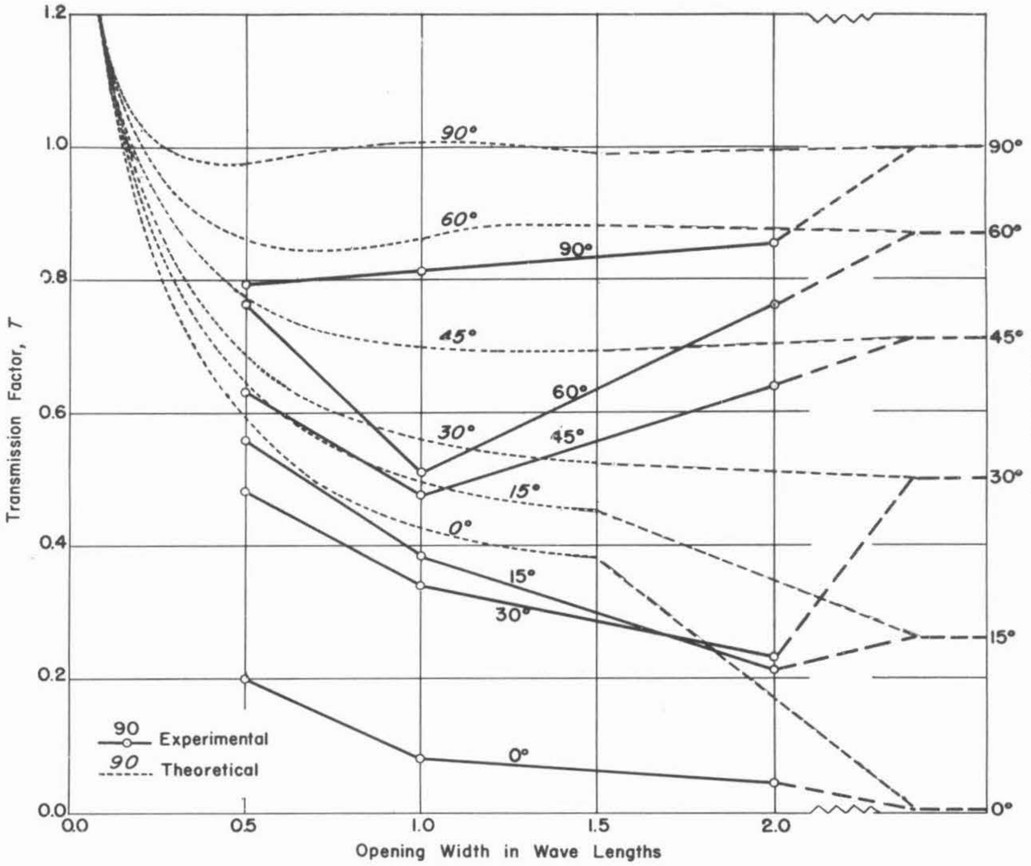

FIG. 4 — THEORETICAL AND EXPERIMENTAL TRANSMISSION FACTORS
Vertical Face Straight Breakwaters

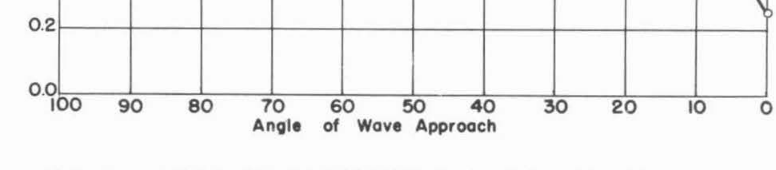

FIG. 5 — RATIO OF EXPERIMENTAL TO THEORETICAL T
Average of Data at 1/2, 1, and 2 Wave Lengths

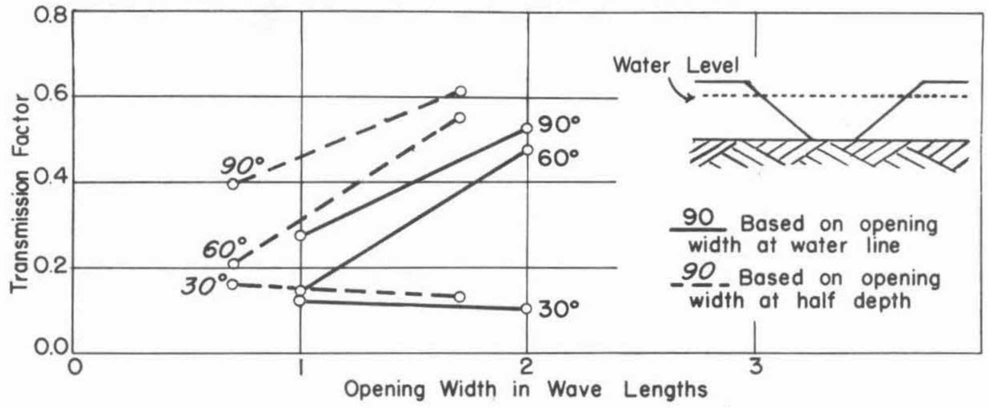

FIG. 6 — EXPERIMENTAL TRANSMISSION FACTORS
Trapezoidal Straight Breakwaters

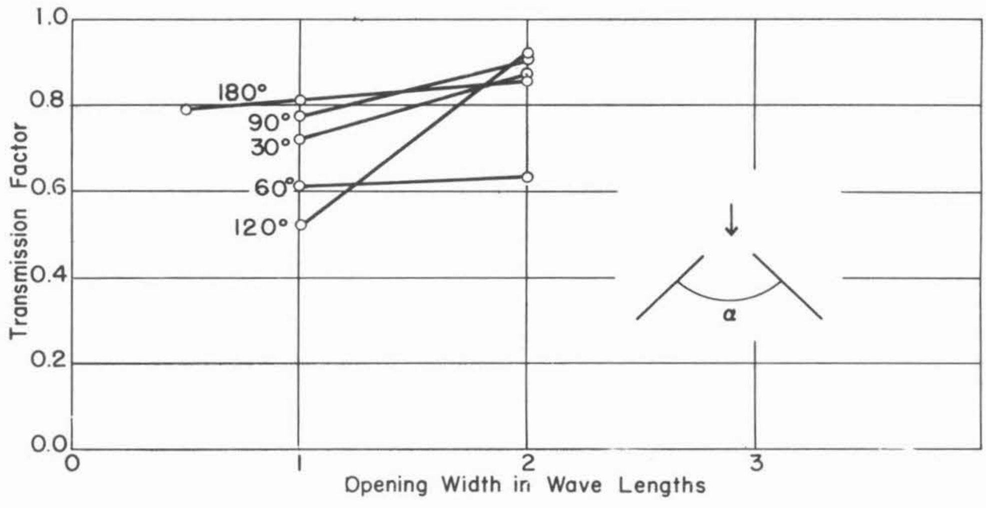

FIG. 7 — EXPERIMENTAL TRANSMISSION FACTORS
Symmetrically Inclined Vertical Face Breakwaters

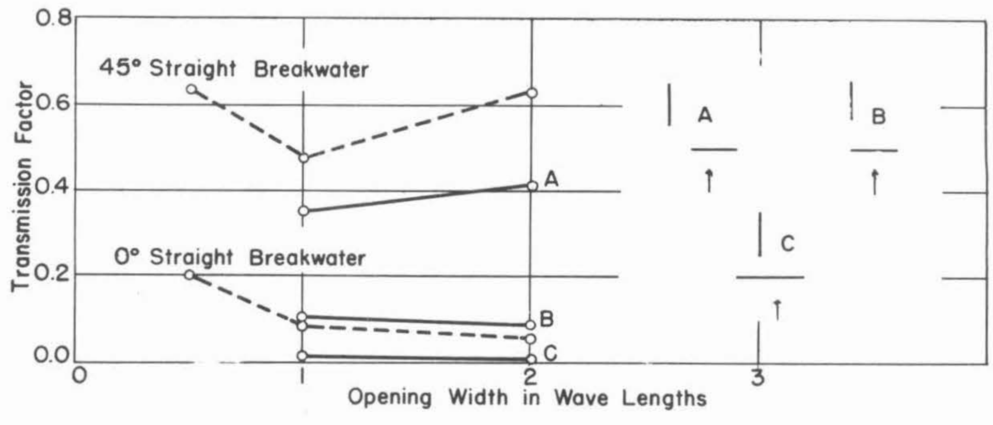

FIG. 8 — EXPERIMENTAL TRANSMISSION FACTORS
Right Angle Vertical Face Breakwaters

definitely below this trend. Since the deviation in energy is 20%, the deviation in wave height, which is the quantity actually measured, is approximately 10%. This deviation is considered to be sufficiently small that the conclusion of good agreement between theory and experiment for approach angles as low as 15° is fully warranted. It may be also concluded that the theoretical values for the 0° case are not substantiated by experiments. As far as practical application of these results are concerned it makes no difference if the 10% difference in wave height is due to systematic error in measurements or to an inaccuracy of the theory, since the deviation is small compared to the many other uncertainties of prototype design. In any case, it appears that the theoretical values may be used for design purposes, and will be conservative compared to the experimental data.

There is no theoretical basis with which to compare the transmission data for the other conditions studied, but in view of the good agreement found for the vertical-face, straight breakwater, it is reasonable to assume that the experimental data is reliable.

The transmission coefficients found for the trapezoidal breakwaters are significantly smaller than those for the vertical-face breakwaters. There are a number of factors which could account for this difference, and it is not possible at this time to ascribe the effect to any one. Some of the possible factors are: (1) effectiveness of the sloping breakwater sides in damping the transmitted waves as they travel the length of the breakwater, (2) special diffractive effects due to the conical breakwater terminii, (3) reflective effects from the termini, (4) damping of incident waves at small incident angles. Since some of these effects are functions of the particular breakwater proportions tested, the data should not be construed as general results applicable to any mound breakwater, but should be viewed as evidence of possible differences which may exist between the idealized vertical face breakwater and practical types of structures. Again, it is seen that the use of the theoretical results for design purposes will be conservative, in the present case leading to an over estimate of wave height of some 30%.

The transmission data for the symmetrically inclined breakwaters correlate, with a few exceptions, with the values for the straight breakwater with 90° wave approach. This result may be expected, since the straight breakwater does not exhibit strong diffraction effects for the range of openings studied, and all the breakwaters of this series have the same projected width of opening in the direction of wave approach.

The transmission data for the right-angle breakwater alignments are especially interesting, since they demonstrate the very great difference in transmission which can result from a small alignment change in some cases. It is further noteworthy that the results are quite similar to the comparable straight breakwater conditions. Thus, case "A" may be compared to the 45°, and case "B" to the 0° straight breakwaters, the terminal points of the two arms of the breakwaters defining the same opening direction with respect to wave approach in each case. This observation suggests that the total energy transmission is primarily a function of gate orientation and width and less so of breakwater orientation.

B. Energy Distribution.

The energy distribution diagrams of Figs. 9, 10, 11, 12, and 13 are the most significant results of this work, since they permit the solution of the design problem of determining wave heights at particular points in a harbor for given breakwater and imposed wave conditions. These results are additionally important because they confirm certain features of earlier results based on the Penney and Price solution for the breakwater gap problem, and because they extend the knowledge of diffraction behavior to include cases of oblique wave approach, a problem which has not been treated previously in a satisfactory manner.

Data points are not shown on the experimental curves because of the small scale necessarily used, however, the curves were drawn through the plotted points with only minor smoothing. Thus, the asymmetry in the 90° cases is due to experimental error, and the irregularities or lobes in the curves are closely indicated by experimental data and are not the result of too much imagination. A detailed discussion of each figure follows:

1. Vertical face straight breakwaters.

Figures 9 and 10 present theoretical and experimental values of I, $(\frac{H_o^2}{H_i^2} \times \frac{R}{\lambda})$, for several gap widths and directions of wave approach. The theoretical data of Fig. 9 have been adapted from data furnished by Prof. Morse, and it is unfortunate that they are for the most part for gap widths on the small side of the most interesting and practical range. It is hoped that current plans for additional theoreti-

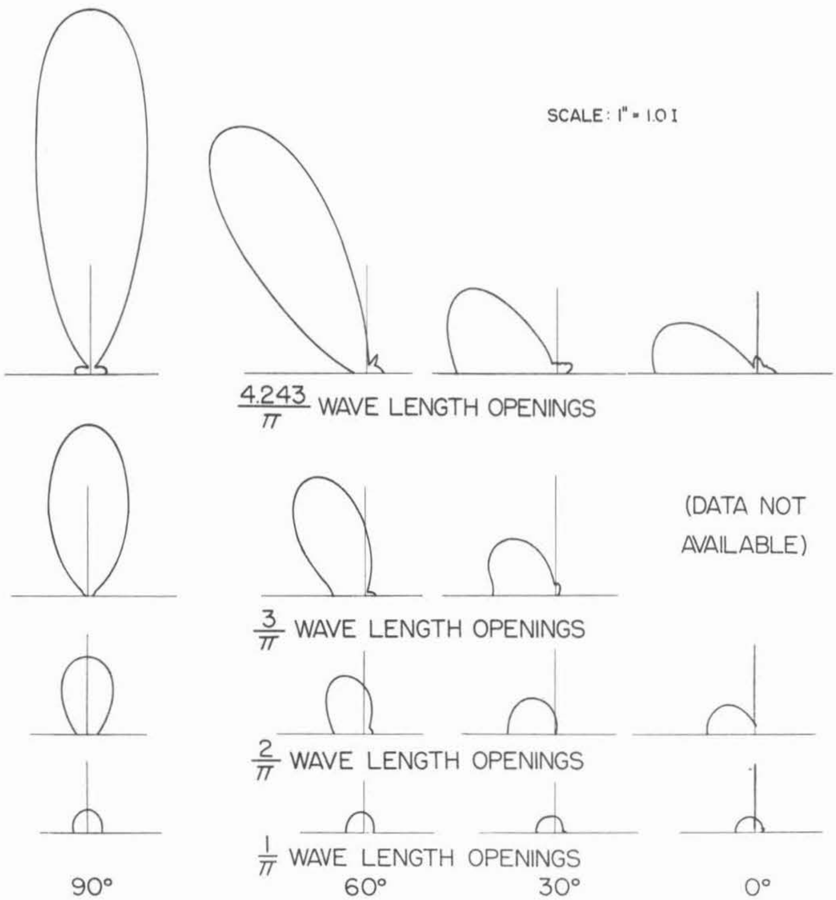

FIG. 9 — POLAR PLOT OF THEORETICAL ENERGY DISTRIBUTION
Plotted from Data Furnished by Prof. Philip M. Morse

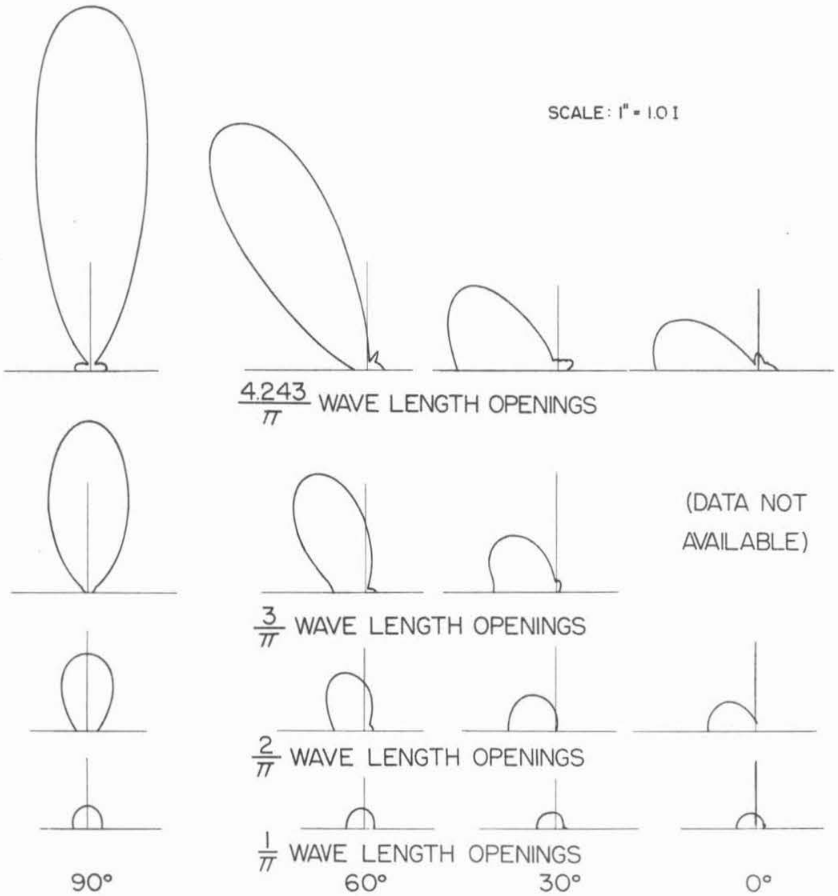

FIG. 9 — POLAR PLOT OF THEORETICAL ENERGY DISTRIBUTION
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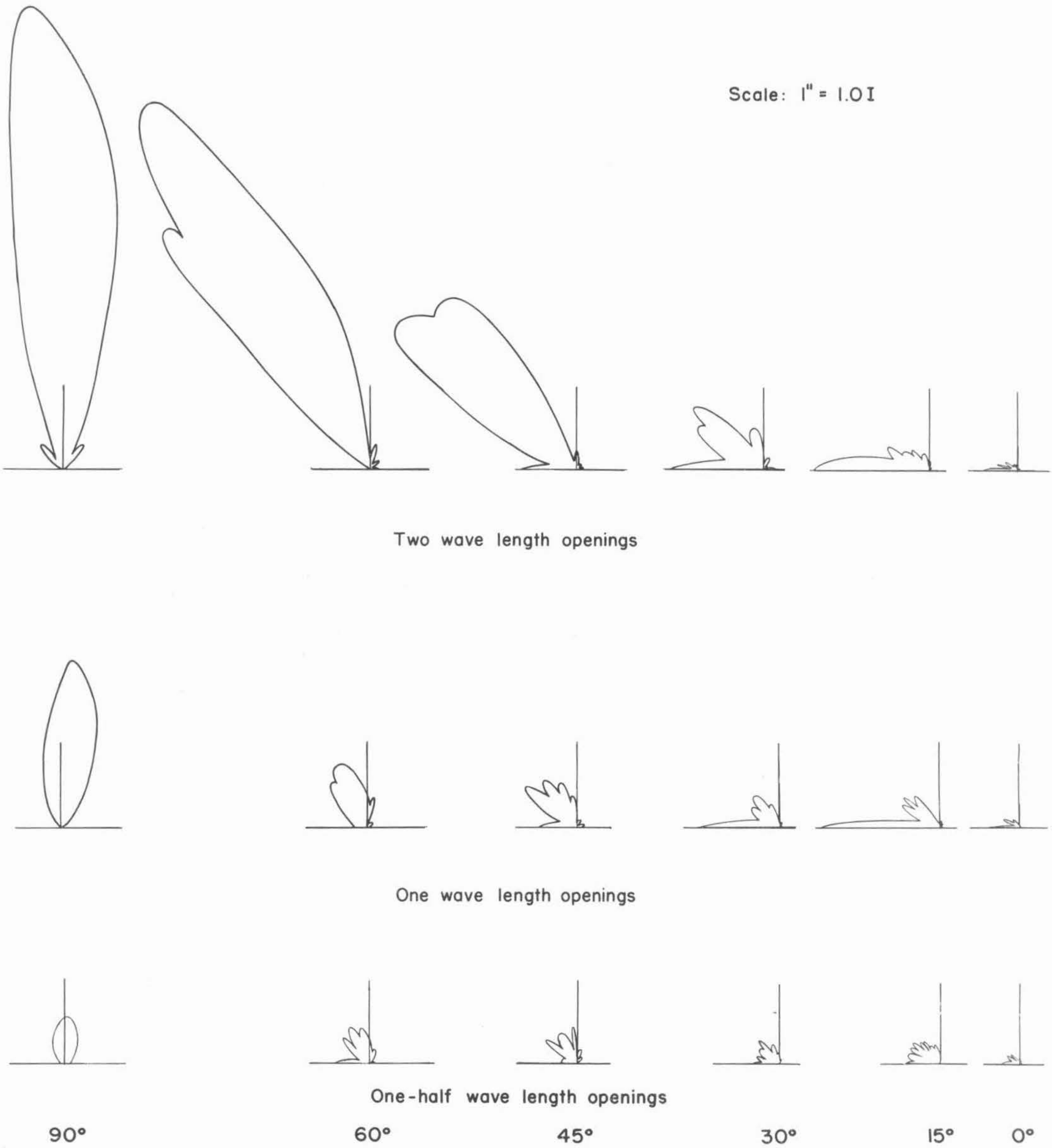

FIG. 10 — POLAR PLOT OF ENERGY DISTRIBUTION
Vertical Face Breakwaters

cal computations will be carried out, and so make available theoretical data for large gap widths.

In general, the experimental data confirms the theoretically predicted characteristics of lower maximum but more uniformly distributed intensity as the gap width and/or wave approach angle are decreased. An interesting check on the quantitative validity of the data may be made be reference to the Penney and Price solution for the gap problem. One outstanding result of this analysis is that the decrease in maximum wave height behind the gap is given approximately by:

$$\frac{H_o}{H_i} = \frac{b}{\sqrt{y\lambda}}$$

where: b = gap width

y = distance behind gap

λ = wave length

It should be noted that for given values of b this expression is only valid for values of y greater than some minimum. Thus, for a gap width of 2 wave lengths, the error is small for values of y greater than b; for a gap width of 5 wave lengths, the expression can be used only for values of y greater than 3b.

In terms of intensity factor, this expression amounts to:

$$I_{max} = \left(\frac{b}{\lambda}\right)^2$$

or, the maximum intensity factor is equal to the square of the opening width in wave lengths.

Although this relation was derived by Penney and Price for gap widths larger than two wave lengths, it is found to fit the theoretical data of Fig. 9 very well. Thus, for the 90° cases of Fig. 9 the agreement is very good down to the smallest opening and, for the 60° cases, using the projected width of opening in the direction of wave approach, the agreement is good down to the opening width of $\frac{2}{\pi}$ wave lengths. Extrapolation of the values of I_{max} for the 30° cases indicates that agreement will be good for openings larger than about 2 wave lengths. The experimental values of I_{max}, while exhibiting some scatter, appear to follow the same relationship. In general, the experimental values are approximately 80% of the theoretical, which is similar to the results of the transmission study. As was pointed out earlier, this indicates a 10% error in determining wave heights.

The most noticeable deviation between theory and experiment is the much greater degree of irregularity of the experimental curves. While the question of experimental error cannot be ignored, it is felt that the numerous lobes of the experimental data are valid quantities and not fictitious. This opinion is heightened by the observation that the plots for various openings for a given direction of wave approach are geometrically similar, and experimental error could hardly result in such a coincidence. At any rate, the details of curve shape have little practical significance, since the difference from crest to trough of a typical lobe is of the order of 20%, indicating a 10% variation in wave height in the vicinity of the lobe.

2. Vertical face converging breakwaters.

The data of Fig. 11, for vertical face symmetrically converging breakwaters are interesting for a number of reasons. First, they corroborate the observation of Blue and Johnson that inclining the arms of a breakwater has virtually no effect on the wave height distribution for included angles less than 90°. Second, the values of I_{max} for 120° and 90° included angles are in good agreement with the theoretical values mentioned in the preceding paragraphs. Reference to Fig. 7 indicates that the measurements for the 60° case are approximately 35% too low, very probably due to an error in incident wave height measurement. If this possibility is taken into account the value of I_{max} and the general distribution of I for the 60° case also compare favorably to the 180°, or straight breakwater. Third and most important, the data show the effect of partially frustrating the diffraction process by preventing free expansion of the wave crests. Thus, the results for the case of 30° enclosed angle show a marked difference from the other conditions studied, the principal characteristic being the increase in wave intensity along the breakwater arms. It should be noted that for this case the intensity factor concept is not valid, and the data cannot be used to compute wave heights at other than the original measuring distance of 5.76 wave lengths from the opening. In

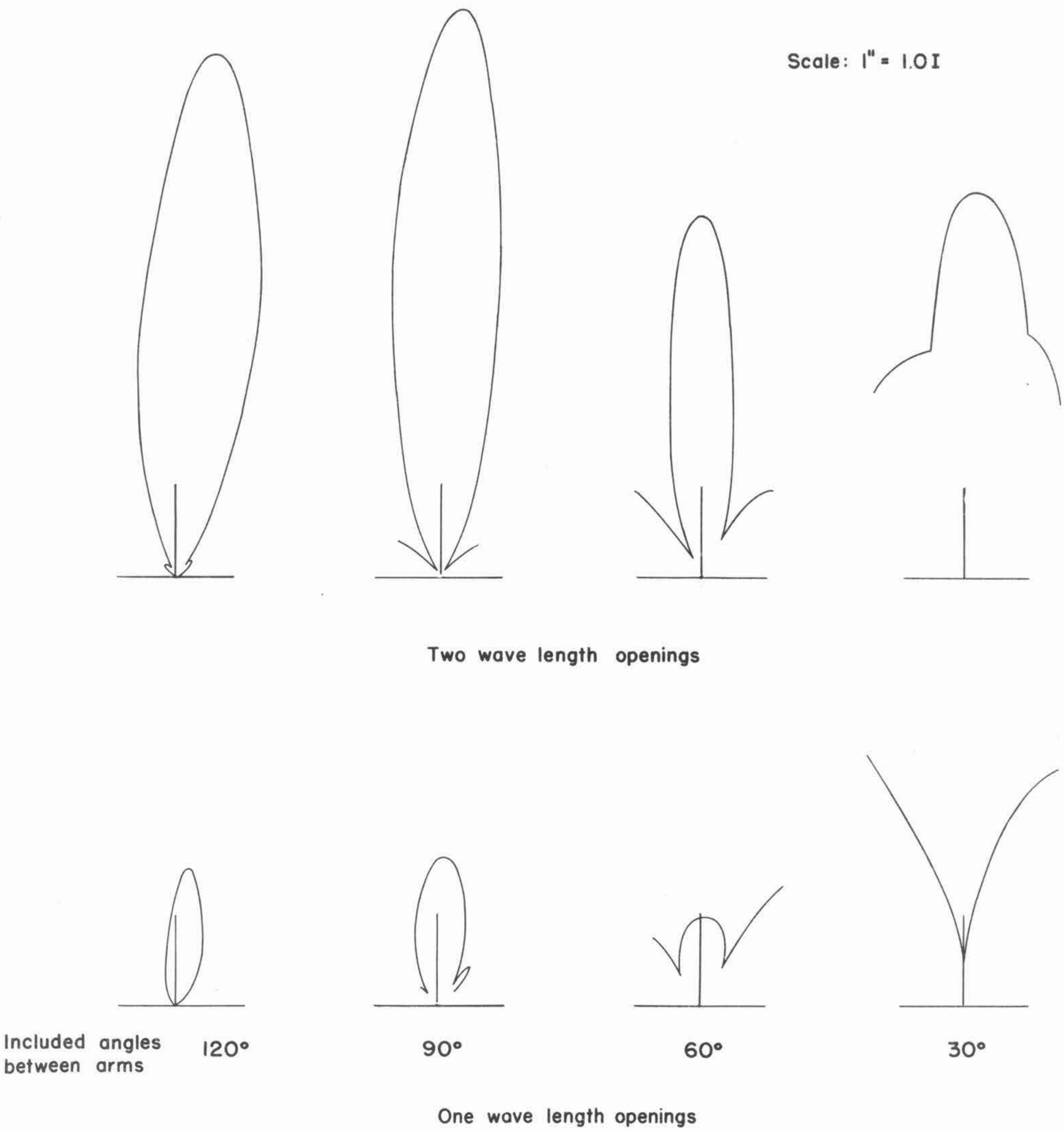

FIG. 11 — POLAR PLOT OF ENERGY DISTRIBUTION
Vertical Face Symmetrical Converging Breakwaters

the limiting case of parallel breakwater arms, there would be no diffraction at all, the wave heights remaining constant for the entire length of the channel; in the 30° case illustrated, the heights must decrease at some rate intermediate between the "zero rate" for a channel and the inverse square root of distance relation for complete diffraction. The data clearly indicates the transition in behavior between 60° and 30° enclosed angles, and so points out an important factor to be considered in the design of converging breakwaters or so-called "wave traps". It is planned to investigate this matter more completely in the future, using a wider range of convergence angles and gap widths.

3. Trapezoidal straight breakwaters.

The results of Fig. 12 differ from those of Fig. 10 in two ways; size and shape of the curves. The difference in magnitude of the intensity factors are to be expected in view of the previously noted difference in transmission, and may be ascribed to the same reasons as previously noted. The increase in number and size of lobes characteristic of these diagrams is believed to be due to the geometry of the breakwater termini. If this is true, the results are not representative of trapezoidal breakwaters in general, but only of the particular proportions investigated. This problem is scheduled for further investigation.

4. Vertical face, right angle breakwaters.

The data of Fig. 13 are included as a purely experimental evaluation of types of energy distribution which may occur for typical

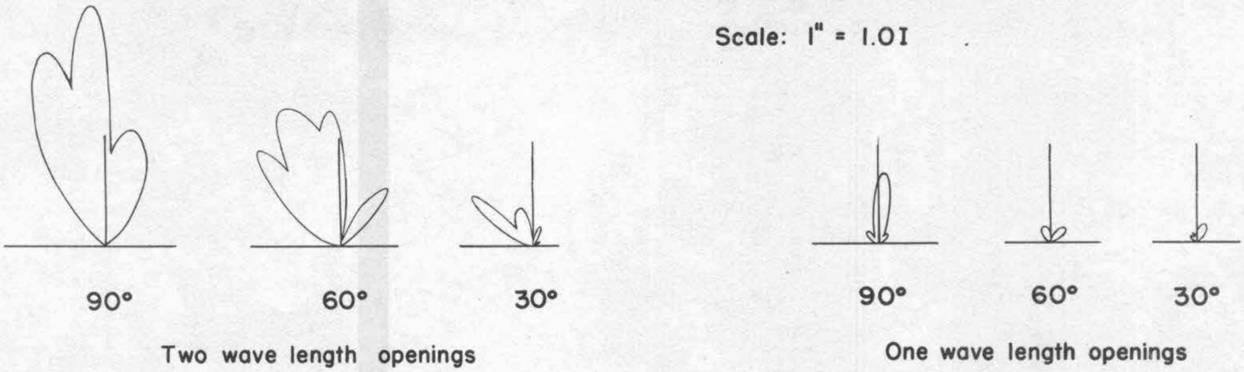

FIG. 12—POLAR PLOT OF ENERGY DISTRIBUTION
Trapezoidal Straight Breakwaters

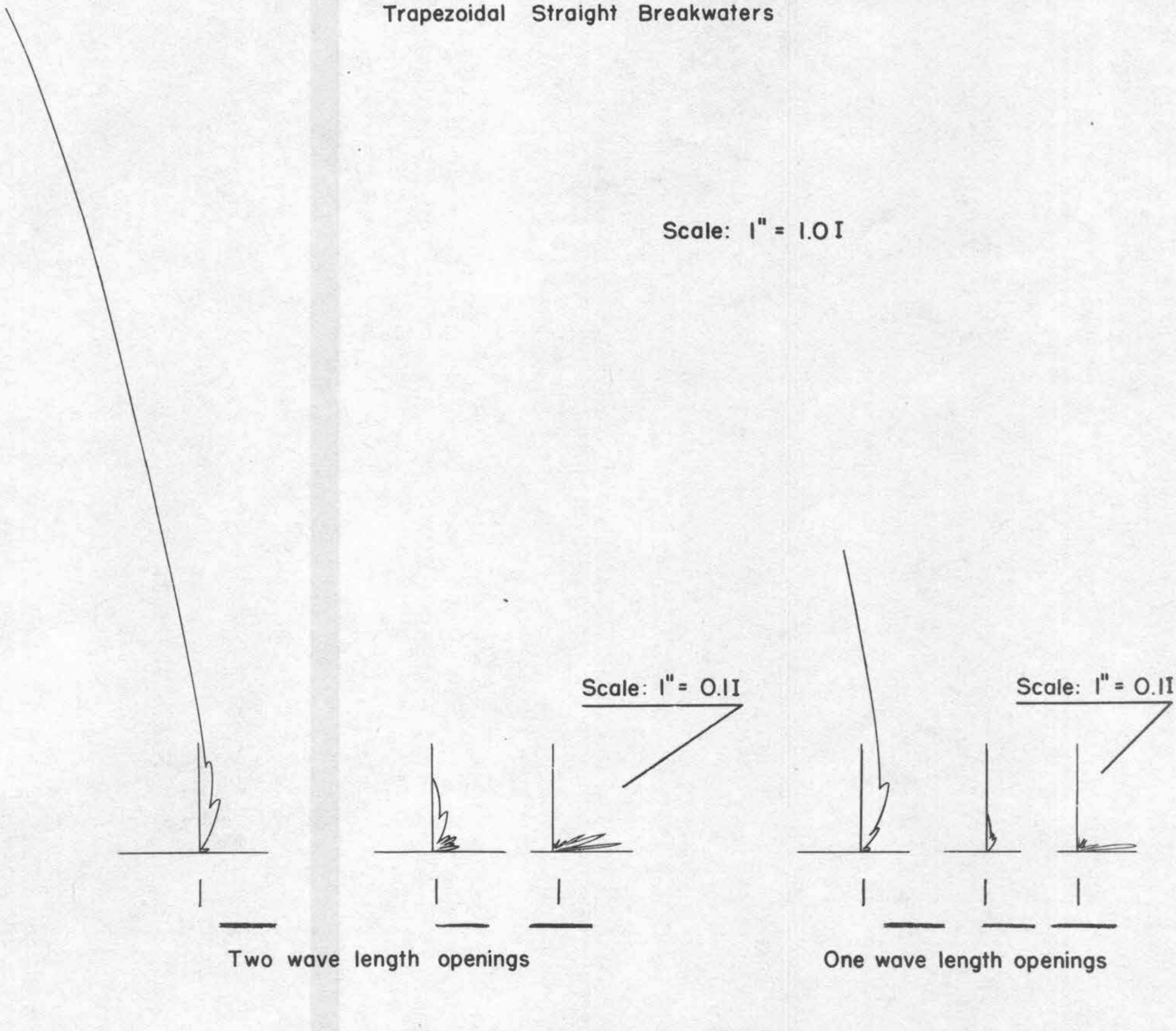

FIG. 13—POLAR PLOT OF ENERGY DISTRIBUTION
Vertical Face Right Angle Breakwaters

asymmetrical breakwater alignments. The origin of the polar plots for these cases is not the center of the breakwater opening as in the other figures, but is the terminus of the breakwater arm oriented perpendicular to the direction of wave travel. This convention results in some skewness of the diagrams for "negative" overlap.

The "negative" overlap cases may be regarded as half-models of the 90° straight breakwater with gap widths of $2\sqrt{2}\lambda$ and $\sqrt{2}\lambda$, respectively. The corresponding theoretical values of I_{max}, 8 and 2, are checked fairly well by the experiment, especially for the smaller opening.

The diagrams for the zero overlap condition are similar in shape and of roughly the same magnitude as those for the 0° straight breakwater. This observation is in agreement with the previously mentioned conclusion that the diffraction process is more sensitive to the angle of wave approach with respect to the alignment of the opening than to the alignment of the breakwater arms which define the opening.

The diagrams for the positive overlap case not only show the remarkable increase in sheltering obtained with such alignments, but also indicate a shift in direction of the maximum disturbance. The latter effect is easily explained: the wave crests after diffraction around the terminus of the seaward arm of the breakwater approach the leeward leg at nearly 90°, and the resulting intensity distribution is as would be expected after diffraction around the leeward terminus.

IV. CONCLUSIONS

A. Application of the Results.

The results obtained to date and presented in this report are in many cases of immediate usefulness for harbor design. Thus, the wave energy transmission data permit a rational evaluation of possible choices of gate size and orientation and of breakwater alignment for a specific development. The wave intensity distribution data enable the designer to predict the relative wave disturbance level in various parts of the harbor and so specify optimum locations for mooring and docking areas and of spending beaches.

Although data is only presented for a restricted range of opening widths, it should be possible to obtain useful approximations for larger openings by extrapolation of the existing curves and use of the relationship for maximum intensity, $I_{max} = (\frac{b}{\lambda})^2$, where b is taken as the projected width of opening in the direction of wave approach. In this regard, it may be mentioned that such an approximate construction for the case of $b = 2.5\lambda$, 90° approach, was found to agree very closely with a solution worked out for this case by Penney and Price.

Several factors must be borne in mind when using the data and methods contained herein:

1. The values of I are valid only for distances from the opening larger than about 3 gap widths.

2. The values of incident wave height and direction must be the values in the immediate vicinity of the opening. Where incident wave data is available only in the form of deep-water values, refraction diagrams must be used to project the waves from deep water to the harbor entrance.

3. Diffraction is not the only factor in determining the energy distribution in a harbor. This question is considered in more detail below:

B. Limitations of the Results.

The principle limitation in the usefulness of diffraction data for harbor design is in the evaluation of the relative importance of diffraction, refraction, and reflection on the overall distribution of wave disturbance in a harbor. For a given harbor, this evaluation requires a knowledge of the wave crest alignments with respect to the bottom contours and the reflecting boundaries. Although the Morse and Rubenstein solution is not adapted, as the Penney and Price solution is, to the determination of wave crest alignment in the entire region behind the opening, both theory and experiment show that the wave crest alignments are very nearly circular arcs at distances from the opening large enough for accurate application of the intensity factor data. Thus, the combination of diffraction and reflection can be considered in a satisfactory manner, the diffraction data specifying primary disturbance distribution and geometrical application of the simple laws of reflection serving to delineate secondary reflected disturbances. Since the nearest reflecting shoreline will usually be at a relatively large distance from the opening, this method should yield sufficiently accurate results.

The evaluation of refraction effects due to changing water depth is more complicated, and in cases where considerable depth change is encountered a great deal of inaccuracy may be expected. A method of handling this problem has been suggested by Dunham, consisting of using diffraction methods to establish a wave crest position behind the opening, and the distribution of energy along this crest, and then projecting the wave crests to the shoreline by purely refraction methods. Dunham proposes this practice in connection with the Penney and Price diffraction method which permits the determination of the wave crest alignment at relatively short distances behind the opening - at least for 90° incidence. This method can also be used with the Morse and Rubenstein solution for any angle of wave approach, but the first wave crest that can be accurately located will be several wave lengths - 6 to 10 - from the opening. If the water depth changes rapidly in this distance, a large error may be introduced in the computations.

In summary, it appears that for most harbor problems, which involve the protection of a gently and uniformly shelving foreshore, the diffraction results may be suitably modified with good accuracy to account for refraction and reflection effects. For unusual cases, where the breakwater opening is located over a submarine ridge or canyon, the refraction effects will be very strong and difficult to combine with the diffraction phenomena. In such cases, model studies may be required to obtain satisfactory disturbance distribution data.

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